Forces and moments generated by aligner-type appliances for orthodontic tooth movement: A systematic review and meta-analysis

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Abstract: The aim of this review was to systematically appraise the evidence on aligner mechanics and forces and moments generated across difference types of aligners. In vitro- laboratory studies for model simulated tooth movement with aligners. Database searches within Medline via Pubmed, Cochrane Central Register of Controlled Trials (CENTRAL), LILACS via BIREME Virtual Health Library. Unpublished literature was also searched in Open Grey, ClinicalTrials.gov (www.clinicaltrials.gov), the National Research Register (www.controlled-trials.com) and Center for Open Science (Open Science Framework), using the terms "aligner" AND "orthodontic". Risk of bias assessment was based on the Cochrane Risk of Bias tool. Random effects meta-analyses were conducted. A total of 447 studies were identified through electronic search and after careful consideration of pre- defined eligibility criteria, 13 deemed eligible for inclusion, while 2 were included in the quantitative synthesis. When palatal tipping of the upper central incisor through PET-G aligners was considered, aligner thickness of 0.5, 0.625 or 0.75 mm was not associated with a significantly different moment to force (M/F) ratio, given a common gingival edge width of 3-4 mm. Aligner thickness does not appear to possess a significant role in forces and moments generated by clear aligners under specific settings, while the most commonly examined tooth movements are tipping and rotation. The findings of this review may be applicable to certain conditions in laboratory settings. Keywords: aligner; force; meta-analysis; moment; systematic review; tooth movement.

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Forces and moments generated by aligner-type appliances for orthodontic tooth movement: a systematic review and meta-analysis

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Structured Abstract

Objectives: The aim of this review was to systematically appraise the evidence on aligner mechanics and forces and moments generated across difference types of aligners.

Settings and Sample population: In vitro- laboratory studies for model simulated tooth movement with aligners.

Materials & Methods: Database searches within Medline via Pubmed, Cochrane Central Register of Controlled Trials (CENTRAL), LILACS via BIREME Virtual Health Library. Unpublished literature was also searched in Open Grey, ClinicalTrials.gov (www.clinicaltrials.gov), the National Research Register (www.controlled-trials.com) and Center for Open Science (Open Science Framework), using the terms "aligner" AND "orthodontic". Risk of bias assessment was based on the Cochrane Risk of Bias tool. Random effects meta-analyses were conducted.

Results: A total of 447 studies were identified through electronic search and after careful consideration of pre- defined eligibility criteria, 13 deemed eligible for inclusion, while 2 were included in the quantitative synthesis. When palatal tipping of the upper central incisor through PET-G aligners was considered, aligner thickness of 0.5 mm, 0.625mm or 0.75mm was not associated with a significantly different moment to force (M/F) ratio, given a common gingival edge width of 3-4 mm.

Conclusion: Aligner thickness does not appear to possess a significant role in forces and moments generated by clear aligners under specific settings, while the most commonly examined tooth movements are tipping and rotation. The findings of this review may be applicable to certain conditions in laboratory settings.

Keywords: aligner, tooth movement, force, moment, systematic review, meta-analysis

1. Introduction

The concept of fabricating aligners on setup casts for orthodontic tooth movement dates back to 1945[1]. Nowadays, the increasing demand for invisible orthodontics and aesthetic considerations, primarily across adult patients, has made the use of thermoplastic aligners quite popular. By the end of the 1990s, two novel thermoplastic aligner systems were introduced allowing for a wide range of tooth movement. The first implemented setups comprising tooth displacements between 0.5 and 1 mm [2]. This required a sequence of 3 aligners per setup step, with increasing thickness. The second, allowed for setup steps to be reduced to approximately 0.2 mm, so that stiffer aligners could be employed[3]. Stereolithographic models and digital setups were implemented, allowing for only one initial impression.

Notwithstanding, forces and moments generated by such aligner-type appliances on teeth remain largely unknown to clinicians. A number of studies compared the force-delivery properties of thermoplastic orthodontic aligners in terms of setup magnitude. It has been stated that setup increments should preferably range between 0.2 and 0.5 mm, depending on the type of thermoplastic material used[4]. Other studies investigated the forces and moments applied on teeth by thermoplastic aligners in a series of movements. During mesiodistal rotation forces were exceeding the suggested load of 20 Nmm[5]. Similar findings were confirmed for intrusion, tipping, and bodily movement [8,14,17].

Clinical behavior of thermoplastic aligner- type appliances is not unaffected by occlusal forces and/ or wear-related properties. The former has been associated with load increases when it comes to rotational moments or intrusive forces[9]. The latter may lead to a considerable force decay and deactivation, which may reach approximately 50 percent after a 2-week period of aligner use[10].

The importance of setup increments in conjunction with the selection of the appropriate thermoplastic foil thickness during aligner manufacturing is pivotal to avoid overloading of teeth during orthodontic movement.

Although a number of studies have attempted to quantify the effect of setup increments and thermoplastic material thickness on aligner mechanics, a systematic review and synthesis of the available evidence is lacking from the existing literature. Therefore, the aim of the present review was to systematically search the relevant literature in order to synthesize the available evidence on aligner mechanics and tooth loading for all types of orthodontic tooth movement with aligner- type appliances.

2. Materials and Methods

2.1. Protocol and registration

A study protocol was specified in advance and registered at PROSPERO (International Prospective Register of Systematic Reviews) no. CRD42019116900.

2.2. Eligibility criteria

Study design: In vitro/laboratory studies, studies related to the forces/moments exerted by aligners, any clinical trial/retrospective cohort study with at least two groups for comparison.

Participants/ Population: Models for simulated tooth movement with aligners were considered for in- vitro studies. Participants undergoing orthodontic treatment with aligners (irrespective of age), if applicable would also be considered.

Intervention: All types of aligners used for orthodontic tooth movement were considered eligible, irrespective of material type, thickness and activation.

Comparator: Any type of comparator will be considered, either non-aligner orthodontic devices or different types of aligners (in terms of design, thickness, inclusion of attachments).

Outcome: Forces and/ or moments generated, complying to any type of tooth movement produced (i.e., rotation, intrusion, torque).

Exclusion criteria: diagnostic accuracy studies comparing predicted and final tooth movement, before- after studies, finite element studies.

2.3. Search strategy and study selection

Detailed electronic search strategies with no language restrictions were developed within 7 databases, as of November 11, 2018: Medline via Pubmed, Cochrane Central Register of Controlled Trials (CENTRAL), LILACS via BIREME Virtual Health Library. Moreover, unpublished literature was searched in Open Grey, ClinicalTrials.gov (www.clinicaltrials.gov), the National Research Register (www.controlled-trials.com) and Center for Open Science (Open Science Framework), using the terms "aligner" AND "orthodontic". Hand searching of the reference lists of the included studies for full text evaluation ~~articles~~ was also conducted. Contact with authors of the original studies was implemented to clarify data when needed.

Eligibility assessment was performed independently and in duplicate by two reviewers (AI, DK) not blinded to the identity of the authors of the original studies, their institutions, or the results of their research. Titles and abstracts were examined first, followed by full text evaluation of the potentially included studies. Disagreements were resolved through consultation with a third author (TE), until a consensus was reached. Full search strategy in MEDLINE via Pubmed is presented in Appendix 1.

2.4. Data collection

Data extraction was performed by one reviewer (AI) in pre- piloted forms. The reviewer who was not blinded to author identity or study origin and all information obtained was confirmed by a second (DK). Data derived comprised on details on: study design, sample size, interventions/ comparators, tooth type and orthodontic movement examined, outcomes (ie forces, moments)

2.5. Risk of bias in individual studies

The assessment of the risk of bias was implemented by one author (AI) after calibration with a second (DK) on 15 percent of the included studies. Entries were confirmed by a second author (DK), and any disagreements were resolved through discussion with a third author (TE). The risk of bias within the included trials was assessed using the Cochrane risk of bias tool in accordance with the Cochrane Handbook for Systematic Reviews of Interventions 5.1.0[11] (a modification of the tool was used to assess risk of bias in in-vitro studies).

2.6. Summary measures and data synthesis

Clinical heterogeneity of the retrieved and eligible for inclusion studies was assessed through the examination of study settings, eligibility criteria, interventions, experimental conditions prior to intervention assignment, laboratory settings and data collection methods. Statistical heterogeneity was first examined through visual inspection of the confidence intervals (CIs) for the treatment effects on forest plots. A chi-square test was also applied to assess heterogeneity; a P value below the level of 10% ($P < 0.1$) was considered indicative of significant heterogeneity[12]. I^2 test for homogeneity was undertaken as well. Only studies with unclear or low risk of bias overall were intended to be included in the quantitative syntheses. Random effects meta-analyses were conducted as they were considered more appropriate to evince the expected heterogeneity and variations in laboratory settings or simulation conditions. Treatment effects were calculated through pooled standardized mean differences (SMDs) with associated 95% Confidence Intervals (95% CIs) and Prediction Intervals where possible (at least three studies).

2.7. Risk of Bias across studies

If more than 10 studies were included in meta-analyses, publication bias was to be explored through standard funnel plots.

2.8. Additional Analyses

Sensitivity analyses were predetermined to explore and isolate the effect of studies with unclear risk of bias on the pooled treatment effect if both low and unclear risk of bias studies were included.

3. Results

3.1. Search Details

A total number of 447 studies were retrieved and the aforementioned inclusion criteria were applied. The flow chart describing the study identification process is presented in Figure. 1. After abstract- and full text reading stage, 13 studies were considered eligible for this review (Table1). All 13 studies were in vitro studies.

3.2. Study design and characteristics

All included studies were published between 2010 - 2018, and reviewed 6 different aligner materials (Biolon, Erkodur, Ideal Clear, Duran, All-In, Invisalign) with foil thickness from 0.3 mm to 1 mm. Six distinctive types of tooth movement were described with the use of the aforementioned aligner combination thickness (Table 1).

3.3. Risk of bias within studies

The risk of bias of the thirteen included in vitro studies was assessed using a modified version of the Cochrane risk of bias tool[11] (Figure 2). Eleven studies[6,8,9,14-20,22] stated clearly the experimental conditions which were comparable between groups. Blinding of the assessors was considered unclear. Losses or non inclusion of specimens were not reported thus no attrition bias was detected and there was no evidence of selective outcome reporting. Based on the aforementioned points these studies were classified as unclear risk of bias. In two studies[13,21], blinding of the assessors was not feasible due to the nature of the interventions thus, these studies were rated as high risk of bias.

3.4. Effects of Interventions, meta-analyses and additional analyses

Effects of interventions

Quantitative synthesis of included studies

Quantitative analysis was only feasible between two of the included studies[8,17], and pertained to palatal tipping movement of maxillary central incisor, generated by PET-G aligners trimmed to a gingival edge width of 3-4 mm. There was no difference between any of the retrieved aligner thickness comparisons with regard to moment to force (M/F) ratio. More specifically, for aligner thickness of 0.5 mm compared to that of 0.75 mm the pooled estimate was a standardized mean difference (SMD) of -3.33 (95%CI: -9.63, 2.96; p-value=0.30; I-squared= 82.0%; Figure 3). Accordingly, no differences to M/F ratio were detected for comparisons between 0.5 mm and 0.625 mm thickness (SMD= -0.43; 95%CI: --4.16, 3.29; p-value= 0.82; I-squared= 84.1%; Figure 4), or 0.625 mm to 0.75 mm (SMD= -0.98; 95%CI: -7.41, 5.46; p-value= 0.77; I-squared= 89.9%; Figure 5), as well.

Qualitative synthesis of included studies

The included studies were examined from three different perspectives regarding aligner thickness, generated tooth movement and aligner material. This arbitrary categorization was implemented simply to facilitate data comprehension.

Aligner thickness

The thickness of plastic foil used for thermoforming PET-G aligners ranged from 0.3 to 1 mm. The forces generated by the thinnest commercially available aligners of 0.5 mm resulted in significant overloading of the periodontal structures[14]. When PET-G aligners of reduced thickness, namely of 0.4 mm and 0.3 mm were used, the aforementioned forces were decreased by 35% and 71% respectively[14]. It has been reported that aligner thickness of 0.3 mm, may reduce rotational stiffness by 76%[15]. Despite the fact that 0.3 mm PET-G aligners seem to exert ideal forces, they are considered unsuitable for clinical use due to deformation[14,15]. Thus, a sequence of aligners including 0.4 mm, 0.5 mm, 0.75 mm has been proposed[14-16] in order to achieve low initial stiffness combined with a steady load. As for 0.625 mm and 0.75 mm PET-G foils, findings indicate that both presented similar mechanical behavior with respect to rotational moments during mandibular canine and maxillary central incisor rotation[15,16] as well as labio-lingual tipping and bodily movement[8,14,17]. Three studies[6,9,18] examined the behavior of 1 mm PET-G aligners and concluded that forces and moments generated were higher than those recommended. Finally, forces applied by 0.7 mm Invisalign system aligners have been reported to lie within the range of acceptable orthodontic forces[22].

Type of tooth movement

Tipping of upper central incisors[13] and lower canine intrusion[20] is feasible with the use of PET-G aligners. On the contrary, three studies[14,18,19] indicated that bodily movement and torque are the most demanding movements to achieve since plain aligners without modifications cannot establish the force couple required. Upper incisor rotation movement with aligners has been frequently coupled with an intrusive force, which may present an increase in magnitude when combined with simulated occlusal forces[6,9,15]. Hahn et al.[6], found that only a slight activation of ±0.17 mm or 0.5 degree per step during rotation could produce ideal forces which have been estimated to range between 0.35 and 0.6 N[23]. Finally, Simon et al. stated that Invisalign aligners bear the potential to deliver force levels of such magnitude, which may produce premolar derotation, bodily movement, molar distalization and torque when combined with appropriate attachment setups[22].

Aligner material

All four studies[6,9,13,18] comparing different PET-G aligner materials of 1 mm thickness reported that aligners vacuum-formed with Biolon (Dreve Dentamid GmbH, Unna, Germany) delivered the highest forces and moments ranging from 1.15 - 6.19 N[13,18] during tipping and 35.3 – 71.8 Nmm[6,9] during rotation, depending on the activation magnitude. The only exception was observed during rotation at low rotation range of ±0.17 mm were the Ideal Clear appliance (Dentsply GAC, Gräfelfing, Germany) exerted the highest values (18,3 – 20,2 Nmm)[6]. Finally, the lowest forces and rotational moments were reported for Erkodur (Erkodent Erich Kopp GmbH, Pfalzgrafenweiler, Germany) at all activation ranges[6,9,13,18].

Finally, three studies[13,21,22] reported the importance of aligner modifications in order to achieve the desired rotation. The use of divots corresponding to the tooth to be treated was found to increase rotational forces by 58%[21], whereas the placement of attachments in teeth with short crowns and few undercuts facilitated as well the delivery of the necessary force system[13].

3.5. Risk of bias across studies

Exploring for publication bias either statistically or graphically was not possible as no more than 3 studies contributed to individual quantitative syntheses.

4.Discussion

To the best of our knowledge, this is the first attempt to systematically appraise the evidence on forces and moments generated by aligner type adjuncts related to orthodontic tooth movement. It was clear that only laboratory studies were identified and subsequently included as the sole source of evidence. Overall, between study heterogeneity and apparent differences in settings, aligner material and type, tooth type and type of movement precluded concrete comparisons between aligner types.

Based on qualitative synthesis, it was evident that one of the thinnest commercially available aligners of 0.5 mm (PET-G aligners) resulted in a non- negligible overloading of teeth which might apparently impact on periodontal structures[14]. Nevertheless, this is compliant with the desired tooth movement. In order to achieve low initial stiffness, a sequence of aligners including an initial aligner of 0.4 mm thickness has been proposed [14-16], while Invisalign (Align Technology, Santa Clara, Calif) utilizes an adjunct of 0.7 mm. Furthermore, the required force couple to achieve bodily movement and torque cannot be established with the use of plain aligners. Thus, modifications such as attachments, divots and cuts are proposed in order to facilitate the desired tooth movement[13,21,22]. Aligners vacuum-formed with Biolon delivered the highest moments and forces when compared to Erkodur, although the results were statistically significant only in specific settings.

Friction phenomena, deformations created at the contact areas during thermoforming as well as polymer material may explain the differences on mechanical behavior between Biolon and Erkodur[6,13]. The former appliances are thermoformed with a pressure of 6 bars, whereas the latter are vacuum- formed~~are vacuum-formed~~ with 0.8 bars[13]. Moreover, according to the manufacturers instructions a spacing foil of 0.05 mm thickness placed between tooth and appliance should be used during thermoforming of Erkodur appliances[6,13]. Although this foil would experience a certain amount of shrinkage after thermoforming, one can assume that its final thickness could be comparable to one activation step.

The quantitative synthesis did not revealed a clear difference between the thinnest commercially available aligners of 0.5 mm and its counterpart of either 0.625 or 0.75 mm in terms of moment to force ratio.. Material of increased thickness may reach higher levels of rigidity, however, this does not result in higher levels of effectively exerted forces that may translate to clinical implications. It has been suggested that the intermediate stage thickness of these adjuncts such as 0.625 may be questionable or even unnecessary in the clinical context[17]. This is in contrast with the existing recommendations for clinical use of 3 consecutive aligners of increasing thickness very close to one another[24]. In essence, in the study of Elkholy et al[8], the authors' intention was to identify possible evidence of translational palatal movement of the central incisor; however, this was not achieved as the final exerted forces showed negligible amounts of bodily movement and was ultimately a result of tipping increments. Moreover, the detected findings were based on aligners with a gingival edge width of 3-4 mm.

Reporting of the included studies was positive overall and allowed for a comprehensive assessment of risk of bias within studies. In general, efforts should be directed in optimizing laboratory conditions that would allow researchers remain blinded when feasible during the assessment of the efficiency of different types of aligners in terms of biomechanical considerations. Moreover, it should be noted that although the risk of selective outcome reporting was minimum given the adequate matching of the reported variables within the methodology section and the results, no study was registered a priori or described a published protocol.

In- vitro studies in laboratory conditions may effectively represent initial tooth movement mechanics. As such, the reported levels of forces or moments are the highest that may have been generated overall. Force decay produced by thermoplastic aligners over a two week period has been documented between 50% of the initial magnitude[10] and a 5- fold decrease[25]. Tooth movement is described by an interaction of forces and moments exerted and as such, the metric "moment to force ratio" is the one that better represents the simulated tooth movement conditions, for tipping and translational movements, irrespective of the anticipated magnitude of the movement. However, gingival edge width of the aligner has been identified as a significant predictor of at least the initial moments/ forces generated by the aligners. Intrusive movements have been reported to be particularly prone to edge width configuration than tipping movements, while edgeless aligners have been associated with decreased force levels[17].

The present review was prospectively registered with an a priori protocol specification and followed a clear and transparent methodology on reported parameters and outcomes. A full search strategy was employed within seven databases, comprising both published and unpublished literature, in an attempt to minimize publication bias. Nevertheless, the review is subject to certain limitations. First, only two studies contributed to quantitative syntheses, over a very specific type of tooth movement on the upper central maxillary incisor and under the spectrum of high degree of heterogeneity. Thus, the findings may only be generalizable to a very limited range of material- tooth interface interactions. Second, data acquired are based on laboratory simulation conditions and cannot be directly transferred to biologic mechanisms of tooth movement within the periodontal ligament. In addition, tooth movement biomechanics have been studied across included studies on a single- tooth specific frame, without consideration of adjacent teeth, elastic modulus of the ligament, occlusal/ mastication forces or soft tissue considerations. Finally, in- vitro studies may suffer from inherent bias due to the lack of standardization of procedures followed to determine the desired effects. In general, specific measuring devices connected to mounted tooth models via a group of sensors and complying to a coordinate system allowing for tooth mobility and simulation of the periodontal ligament have been used. Apparently, any variation within the described laboratory set- up across individual studies may result in heterogeneous results. As such and following guidelines from clinical research, there is an overriding need for the development of consistent study protocols prior to study commencement, as well as for the agreement on the experimental settings and the most valuable core outcome sets to be universally used[26].

5. Conclusions

Use of fabrication material of the aligners was confined to different types of PET-G. Aligner thickness does not appear to play a significant role over initial forces and moments generated by thermoplastic aligners. Foils have been typically reported to range between 0.5mm and 1mm. The most widely examined tooth movements are tipping and rotation, with rotational forces ascending to a much higher level. However, the findings of this review may be applicable to specific conditions and tooth movements in laboratory settings. Overall, there is a need for standardized protocols, types of movements or design of the aligners in order to inform the existing evidence with more conclusive outcomes.

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Conflict of Interest

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Table 1. Characteristics of the included studies (n=13).

id	Author & Year of Publication	Study Design	Sample size/teeth type	Groups under Comparison	Interventions	Outcomes
1	Brockmeyer et al 2017	in vitro	total n=45 aligners, same thickness 1mm Biolon uncut n=5, z11 n=5, z12-21 n=5 Erkodur uncut n=5, z11 n=5, z12-21 n=5 IdealClear uncut n=5, z11 n=5, z12-21 n=5 upper central incisor	material vs cut, deflection distance vs material, deflection distance vs cut	thermoplastic aligners modified by incisal cuts	horizontal force component magnitude, vertical force component magnitude in labial and palatal translation of upper central incisors
2	Elkholy et al 2015	in vitro	total n=27 aligners Duran 0.5mm (n=3), 0.625mm (n=3), 0.75mm (n=3) Erkodur 0.5mm (n=3), 0.6mm (n=3), 0.8mm (n=3) Track-A 0.5mm (n=3), 0.63mm (n=3), 0.8mm(n=3) upper central incisors	forces delivered aligner/ thickness	different aligner thickness n material Duran 0.5mm (n=3), 0.625mm (n=3), 0.75mm (n=3) Erkodur 0.5mm(n=3), 0.6mm (n=3), 0.8mm (n=3) Track-A 0.5mm(n=3), 0.63mm (n=3), 0.8mm(n=3)	forced and moments magnitude to upper central incisor for labial and palatal translation
3	Elkholy et al 2016	in vitro	total n=15 Duran 0.3mm(n=3) 0.4mm (n=3) 0.5mm (n=3) 0.625mm (n=3) 0.75(n=3) upper central incisors	forces delivered aligner/ thickness	reduced thickness aligners Duran 0.3mm (n=3) 0.4mm (n=3) 0.5mm (n=3) 0.625mm (n=3) 0.75(n=3)	forces and moments delivered during labiopalatal movement of upper central incisor
4	Elkholy et al 2017 (AJODO)	in vitro	total n=15 Duran 0.5mm(n=3), 0.625mm(n=3), 0.75mm(n=3) vs 0.3mm(n=3), 0.4mm(n=3) upper central incisors	forces applied by 0.3/0.4mm aligners vs conventional >0.5mm	reduced thickness aligners 0.4, 0.3mm Duran 0.5mm(n=3), 0.625mm(n=3), 0.75mm(n=3) vs 0.3mm(n=3), 0.4mm(n=3)	forces and moments delivered during mesiodistal derotation of upper central incisor

5	Elkholy et al 2017 (J Orofac Orthop)	in vitro	total n=9 Duran 0.5mm(n=3), 0.625mm(n=3), 0.75mm(n=3) mandibular canine	forces delivered aligner /thickness	Duran 0.5mm(n=3), 0.625mm(n=3), 0.75mm(n=3)	forces and moments delivered during mesial and distal derotation of mandibular canine
6	Gao et al 2017	in vitro	total n=27*2=54? Duran 0.5mm/ 0-1 width n=3 Duran 0.5mm/3-4 width n=3 Duran 0.5mm/ 6-7 width n=3 Duran 0.625mm/ 0-1 width n=3 Duran 0.625mm/ 3-4 width n=3 Duran 0.625mm/ 6-7 width n=3 Duran 0.75mm/ 0-1 width n=3 Duran 0.75mm/ 3-4 width n=3 Duran 0.75mm/ 6-7 width n=3 upper central incisor	edge width comparison / aligner thickness	different aligner thickness width Duran 0.5mm/ 0-1 width n=3 Duran 0.5mm/3-4 width n=3 Duran 0.5mm/ 6-7 width n=3 Duran 0.625mm/ 0-1 width n=3 Duran 0.625mm/ 3-4 width n=3 Duran 0.625mm/ 6-7 width n=3 Duran 0.75mm/ 0-1 width n=3 Duran 0.75mm/ 3-4 width n=3 Duran 0.75mm/ 6-7 width n=3	forces and moments delivered during maxillary central incisor palatal tipping and intrusion
7	Hahn et al 2010 (Angle)	in vitro	n=15 Ideal Clear 1mm n=5 Erkodur 1mm n=5 Biolon 1mm n=5 upper central incisor	forces delivered aligner material	different aligner material	force system and moments produced by 3 different types of plastic aligners during rotation
8	Hahn et al 2010 (EJO)	in vitro	n=15 Ideal Clear 1mm n=5 Erkodur 1mm n=5 Biolon 1mm n=5 upper central	forces delivered aligner material	different aligner material	force system and moments produced by 3 different types of plastic aligners during torque
9	Hahn et al 2011	in vitro	n=20 Biolon 0.75mm n=5 Biolon 1mm n=5 Erkodur 0.8mm n=5 Erkodur 1mm n=5 upper central	forces delivered material/ with and without simulated occlusal forces	different aligner material + occlusal forces	forces produced by 2 different types of aligners with and without simulated occlusal forces during rotation of upper central incisors

10	Li et al 2016	in vitro	n=5, Erkodur 1mm activation 0.2mm n=1 activation 0.3mm n=1 activation 0.4mm n=1 activation 0.5mm n=1 activation 0.6mm n=1 upper central	forces delivered between various amounts of activation aligners	aligners with various amounts of activation	forces delivered between various amounts of activation aligners and attenuation during lingual bodily movement of upper central incisor
11	Liu et al 2018	in vitro	n=55, Duran 0.8mm thickness G0 control n=5 G1 intrude mand canines by 0.2mm n=5 G2 intrude 4 mand incisors by 0.2mm n=5 G3 intrude canines and inc by 0.2mm n=5 G4 intrude can 0.1mm, lat inc 0.15mm, centr inc 0.2mm plus attachments on 1st and 2nd premolars and 1st molars	G0,G1,G2,G3,G4	aligners with different activation	forces delivered between various types/amount of aligner activation during intrusion of lower anterior
12	Mencattelli et al 2015	in vitro	All in, Micerium n=3 - aligner with no forces n=1 - aligner without divot n=1 - aligner with divot n=1 maxillary central incisor	with divot/ without divot	aligner with divot	forces delivered from aligner with divot during rotation
13	Simon 2014	in vitro	n=970 aligners (60 series/30 patients) Invisalign incisor torque*, n=10 patients (split mouth torque<10o +attachment) premolar derotation*, n=10 patients (split mouth derotation<10o + attachment) molar distalization*, n=10 patients (split mouth distalization<1.5mm + attachment) *20 tooth movements (2 per patient)	with/ without attachments in specific movements: torque, derotation, distalization	with/without attachments	initial force systems that are delivered by an individual aligner, force systems generated by a series of aligners, influence of auxiliaries (attachments, power ridges) on the force transfer

FIGURE LEGENDS

Figure 1. Flow diagram of article retrieval.

Figure 2. Risk of bias summary outlining judgment of risk of bias items for each of the included studies. The plus sign indicates low risk of bias; the circle with question mark indicates unclear risk of bias; the minus sign indicates high risk of bias.

Figure 3. Random effects meta-analysis for the effect of aligner thickness on moment to force (M/F) ratio, for palatal tipping of the upper central incisor (aligner thickness: 0.5 mm versus 0.75 mm).

Figure 4. Random effects meta-analysis for the effect of aligner thickness on moment to force (M/F) ratio, for palatal tipping of the upper central incisor (aligner thickness: 0.5 mm versus 0.625 mm).

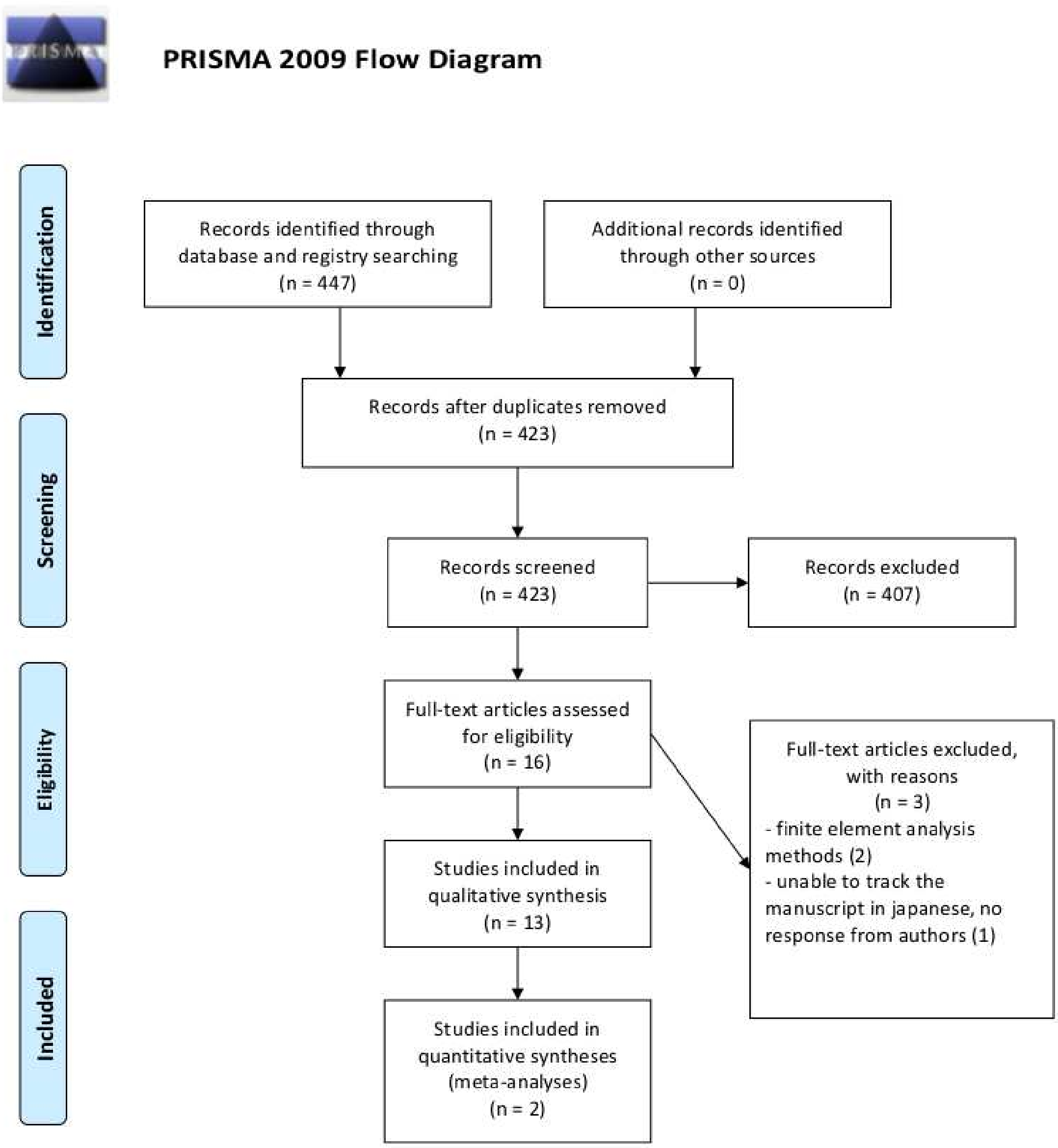
Figure 5. Random effects meta-analysis for the effect of aligner thickness on moment to force (M/F) ratio, for palatal tipping of the upper central incisor (aligner thickness: 0.625 mm versus 0.75 mm).

Appendix 1.

MEDLINE search
Date: November 9, 2018
Limits: no language restriction applied
Publication date: no restriction
Search Builder: ‘All Fields’
Two consecutive searches combined with “AND” Boolean operator, using “OR” between free text terms or keywords:

1. invisalign
2. aligner
3. aligners
4. aligner*
5. thermoplastic aligner
6. thermoplastic aligner*
7. 1 OR 2 OR 3 OR 4 OR 5 OR 6
8. force
9. forces
10. force*
11. orthodontic movement
12. orthodontic movements
13. orthod* movements
14. orthodontic force
15. orthodontic force*
16. orthodontic moments
17. orthodontic moment
18. moment
19. moments
20. torque
21. torque control
22. 8 OR 9 OR 10 OR 11 OR 12 OR 13 OR 14 OR 15 OR 16 OR 17 OR 18 OR 19 OR 20 OR 21
23. 7 AND 22

Figure 1. Flow diagram of article retrieval.



From: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). *Preferred Reporting Items for Systematic Reviews and Meta-Analyses*: The PRISMA Statement. PLoS Med 6(7): e1000097. doi:10.1371/journal.pmed1000097

For more information, visit www.prisma-statement.org.

Figure 2. Risk of bias summary outlining judgment of risk of bias items for each of the included studies. The plus sign indicates low risk of bias; the circle with question mark indicates unclear risk of bias; the minus sign indicates high risk of bias.

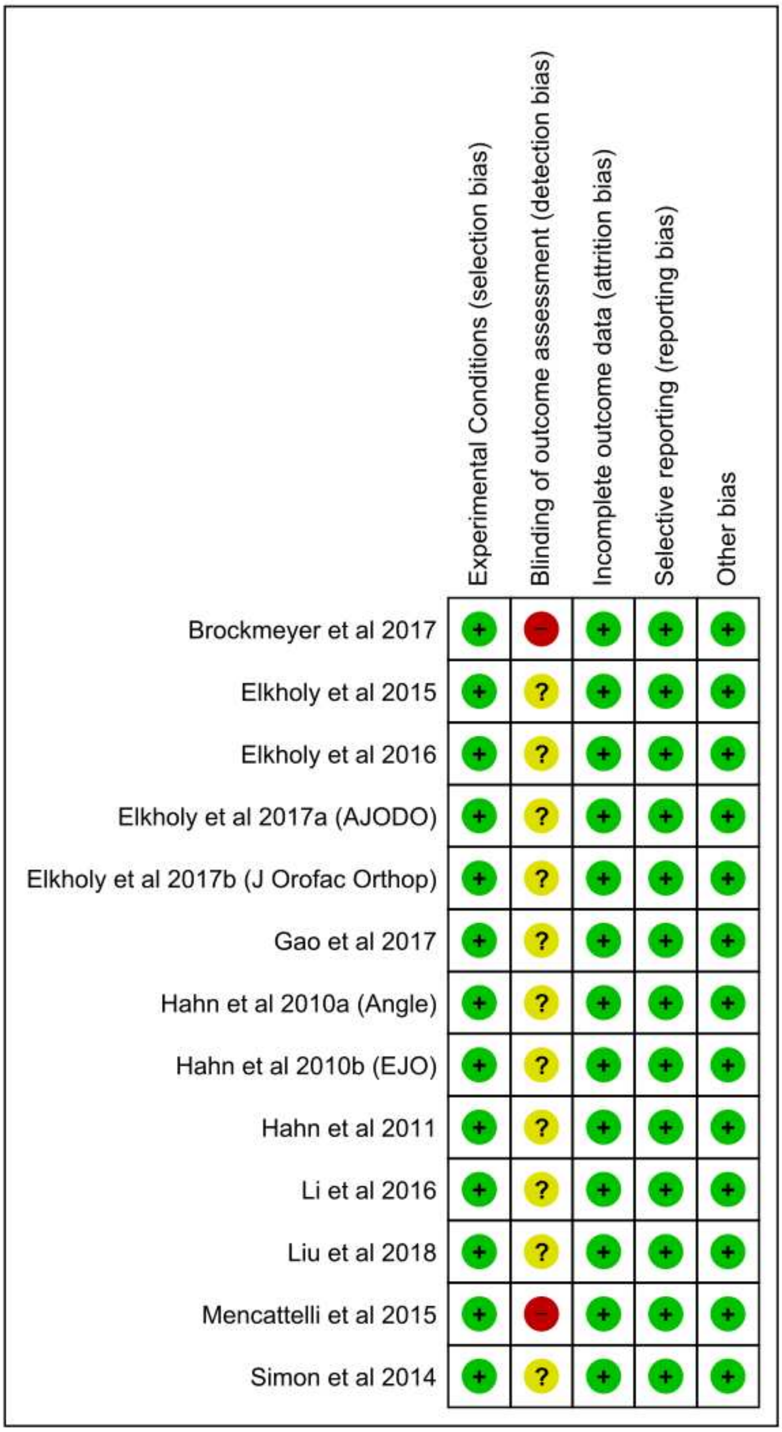


Figure 3. Random effects meta-analysis for the effect of aligner thickness on moment to force (M/F) ratio, for palatal tipping of the upper central incisor (aligner thickness: 0.5 mm versus 0.75 mm).

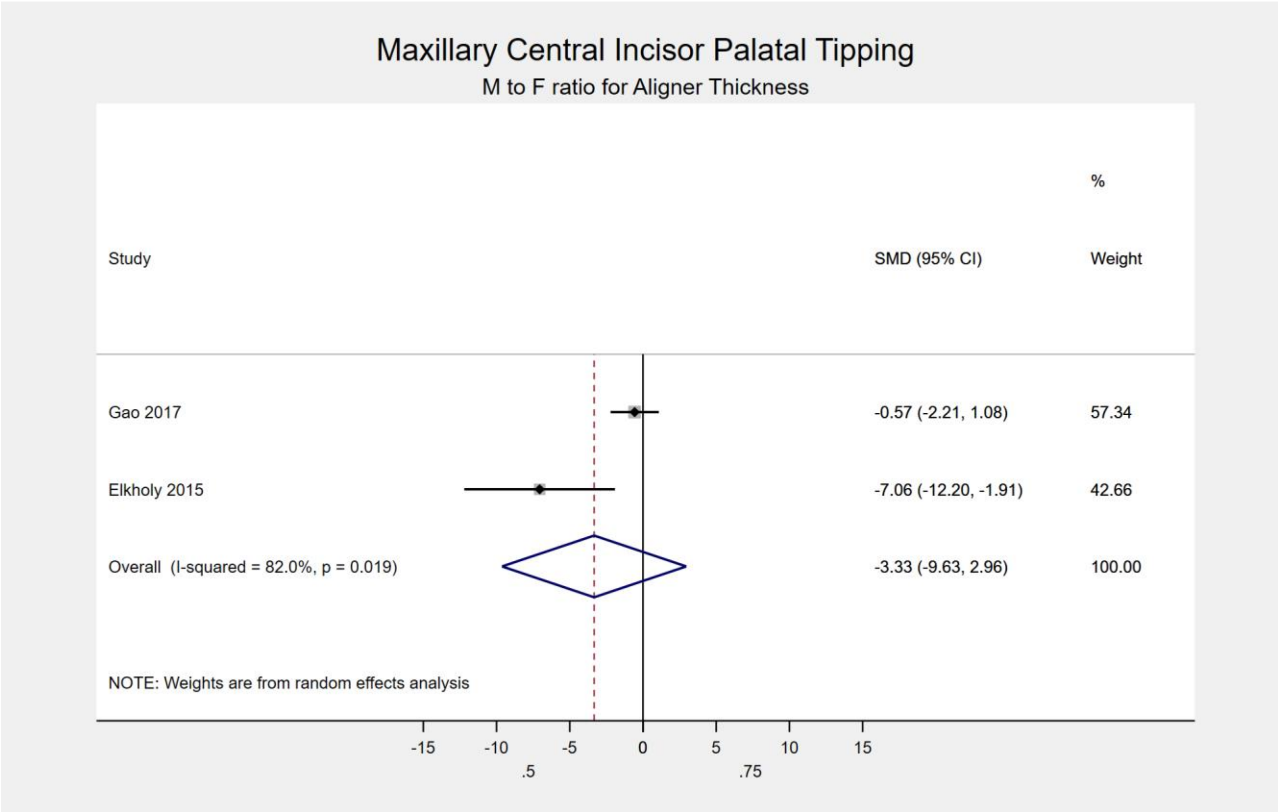


Figure 4. Random effects meta-analysis for the effect of aligner thickness on moment to force (M/F) ratio, for palatal tipping of the upper central incisor (aligner thickness: 0.5 mm versus 0.625 mm).

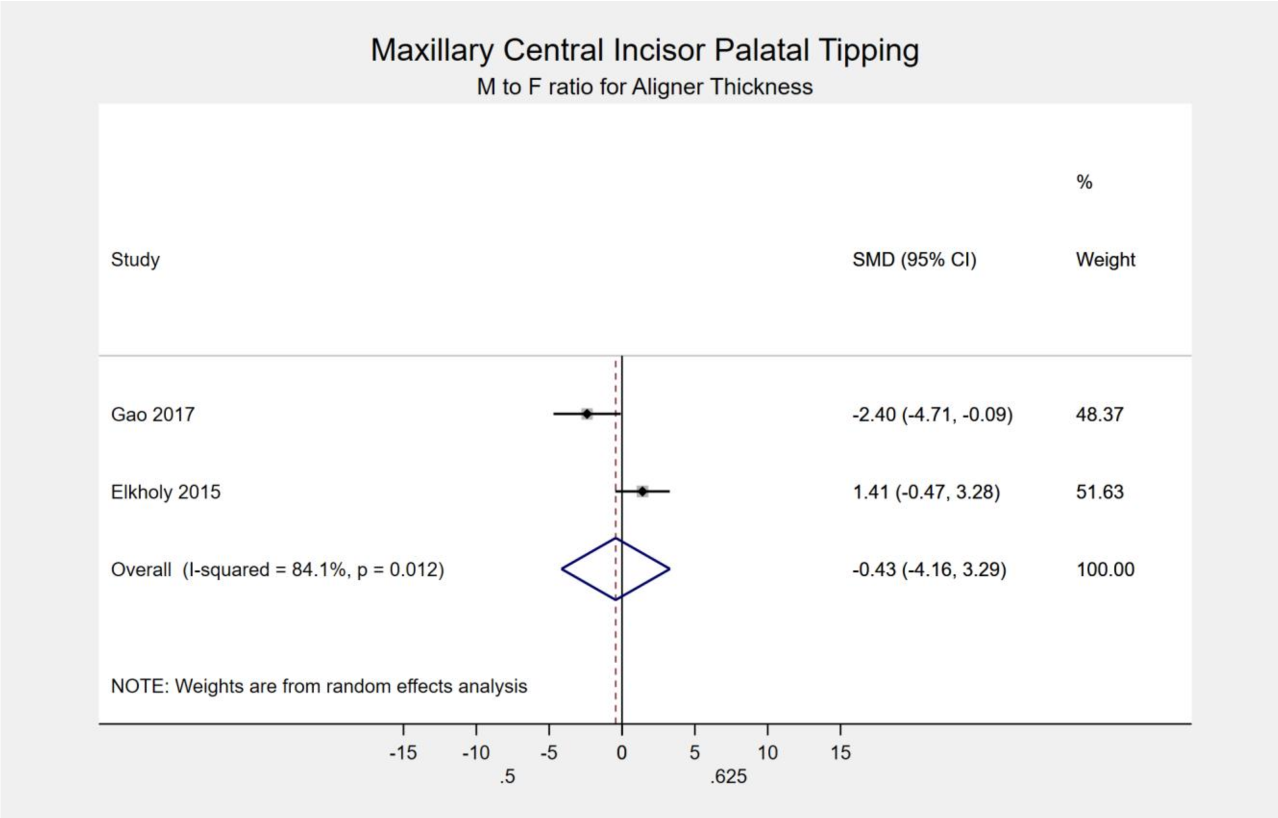


Figure 5. Random effects meta-analysis for the effect of aligner thickness on moment to force (M/F) ratio, for palatal tipping of the upper central incisor (aligner thickness: 0.625 mm versus 0.75 mm).